

SOLID DIVERT BREAKTHROUGHS THAT ENABLE MISSION FLEXIBLE TMD INTERCEPTORS

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Abstract

This paper describes technology breakthroughs in solid divert propulsion that provide extensive mission flexibility to theater missile defense (TMD) interceptors over previous solid propellant divert systems. TMD interceptors must cover large battlespaces to minimize the total number of launchers and deployed missiles. They must defend against a broad set of targets, from short to long ranges. Effectiveness against current and emerging TMD targets is ensured when a fully controllable Divert and Attitude Control System (DACS) is used to maneuver the interceptor to impact. Operational requirements demand this DACS use solid propellant for user safety and cost minimization. Aerojet has recently accomplished several technology breakthroughs which demonstrate a solid DACS can be built with the mission flexibility of a liquid. This DACS called EXCELS (Endo, eXo, Controllable, Extinguishable, Lightweight, Solid), is the industry's first truly controllable solid DACS.

Aerojet's EXCELS DACS has been under development since 1991 with IR&D funding. Since then, four key development tests have been performed that validate the technology. Results are summarized in this paper. Aerojet is now supporting the BMDO, Navy and Army with contracts to further develop the EXCELS DACS for the SM-3 Block 2 Risk Reduction effort and the Atmospheric Interceptor Program (AIT). DACS development progress made on these programs in Winter and Spring 1998 are included in this paper.

Introduction

This paper describes technology breakthroughs in solid divert propulsion that provide extensive mission flexibility to theater missile defense (TMD) interceptors over previous solid propellant divert systems. TMD interceptors must cover large battlespaces to minimize the total number of launchers and deployed missiles.

They must defend against a broad set of targets with short to long ranges. Divert and Attitude Control Systems (DACS) provide propulsive controls to flyout predicted intercept errors and to guide the kinetic warhead (KW) to a direct hit intercept. Effectiveness against current and emerging TMD targets is ensured when a fully controllable DACS is used to maneuver the interceptor to impact. Operational requirements demand this DACS use solid propellant for user safety and cost minimization. Aerojet has recently accomplished several technology breakthroughs which demonstrate a solid DACS can be built with the mission flexibility of a liquid. This DACS called EXCELS (Endo, eXo, Controllable, Extinguishable, Lightweight, Solid), is the industry's first truly controllable solid DACS.

EXCELS DACS provides the following benefits to the user:

- extended missile interceptor battlespace;
- flexibility to fly varying mission profiles without hardware changes;
- precise target engagement and aim-point control;
- reduced propellant mass for long flyouts.

EXCELS extends interceptor battlespace and mission flexibility by extinguishing divert propellant combustion and/or deeply throttling the propellant burn rate. As a result, the user can turn combustion on and off or adjust maximum thrust levels at will. Extinguishment and reignition enable divert mission times of 300 sec and beyond. Cyclic deep throttling enables divert mission times approximating 100 sec and is also used for energy management in the pre-endgame of a long extinguishment-type mission. These advancements provide a 10-fold increase in solid DACS mission duration over the previous state of the art, reduce DACS propellant weight and give impulse margin for target uncertainties at intercept.

EXCELS DACS ensures precise target engagement with breakthroughs in proportionally controlled thruster technology. These thrusters

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use variable area pintle throats to precisely adjust thrust from 0-100%. The KW G&C system may command any thrust vector from 0-360 degrees as well as 0-100% net thrust level. This control over thrust and direction precisely guides (diverts) the KW with the selected aim-point during end-game maneuvers. Seeker jitter is reduced throughout the mission because our proportionally controlled thrusters give the KW a "soft ride" with a linear ramp thrust rise.

Objectives for development of our solid DACS technology were defined in 1993. We anticipated a wide range of uses, interviewed customers and incorporated lessons learned from our liquid DACS experience in developing objectives for the fully controllable EXCELS DACS. The objectives are to:

- Maximize flight time to enable increased battlespace;
- Be adaptable to multiple interceptor missions with flexibility to adjust propellant burn profiles (short missions, long missions, variable missions);
- Have sufficient flexibility in the operation of the DACS to allow requirement changes right up to and within the interceptor flight;
- Use our controllability to alleviate seeker, avionics and structure requirements;
- Reduce propellant mass required to complete DACS mission.

We drove to a single technology applicable to endo- and exo-atmospheric interceptors. The EXCELS tradename describes the inherent flexibility in our product, Endo, eXo, Controllable, Extinguishable, Lightweight, Solid DACS. We apply the EXCELS DACS technology to many different configurations for separating and non-separating interceptors. Two key configurations of EXCELS are shown in Figure 1. The DACS on the left is our throttling-only DACS that incorporates the divert and Attitude Control System (ACS) thrusters on a common chamber and throttles combustion pressure during coast modes to preserve propellant for divert periods. It is well suited for Exo missions where ACS thrust requirements reduce during coast modes and durations in the 100 sec range are desired. We have applied this configuration to our SM-3

DACS that is in development for the Standard Missile Company, BMDO and the Navy's Theater Wide Program under the Divert Risk Reduction Activity.

The unit on the right in Figure 1 extinguishes propellant between flyout divert periods to preserve propellant and minimize thermal loads. This unit provides continuous ACS operation independent of divert by storing hot gas in a thermally managed accumulator. The accumulator is recharged each time the divert is fired. This configuration is well suited to endo missions because high ACS thrust is available when the divert is off. We have applied this configuration to our AIT DACS that is in development for the Army SMDC's and BMDO's AIT Test Bed Program.

Our throttling SM-3 EXCELS DACS is ignited only once and then controlled to varying mission requirements by throttling combustion pressure up and down as shown in Figure 2. During coast, each thruster flows 25% of the throttled flowrate so that the thrust is nulled and no perturbations are input to the KW. Each time a divert period is commanded, the thrusters adjust the pressure back to high pressure and divert thrust is delivered. High combustion pressure is maintained during the endgame so that full thrust is available with fast response. With our interactive control system the user can select the time at which divert periods take place as well as the duration of each period.

Our extinguishable AIT EXCELS DACS is ignited and extinguished several times over a mission to extend propellant use over missions in the 300 plus sec range as shown in Figure 3. Each time a divert period is commanded, the divert grain is ignited and combustion gas raises the pressure of the divert and ACS accumulator together. When full pressure is reached, divert thrust is delivered or the grain is extinguished as desired. Again, with our interactive control system, the user can select the time at which divert periods take place as well as the duration of each period. The combustion can also be throttled in this system for short missions and in the early part of the endgame like the SM-3 DACS configuration.

The net benefit of the throttling and extinguishment features is a reduction in propellant mass for long flyouts which translates to reduced KW weight and higher V_{bo} .

Our EXCELS features four orthogonal, proportionally controlled thrusters to adjust thrust to any level between null and the max rating and to select any vector over 360 degrees as shown in Figure 4. Additionally, less than full thrust can be delivered on- or off-axis as desired by the G&C to accomplish minuscule impulse bits, for accurate aim-point selection and to adjust real time for varying jet interaction (JI) effects on the KW body.

EXCELS proportionally controlled thrusters provide a "soft ride" for the KW that is unachievable with typical on/off thrusters. The gradual thrust rise rate, shown in Figure 5, significantly reduces shock magnitudes delivered to the KW. Therefore, seeker jitter is controlled, aim-point selection is improved and KW structure weight can be reduced. The chart compares the gradual 8-msec rise rate demonstrated in our thrusters to the <1-msec rise rate typical of on/off thrusters (the period of poppet travel after the threshold for movement is achieved) that imparts significant shock to the KW.

We developed this controllable solid DACS on our EXCELS IR&D program beginning in 1991, concluding with a full system test in 1996 as shown in the Figure 6 Schedule. Each year we matured the technology with higher level demonstrations. After single pintle divert thruster tests in 1991, we moved to multi-thruster tests, flight-weight divert tests, ACS subsystem tests and then culminated the development with a full system hot-fire at the end of 1996. Now we have transitioned the development to SM-3 and AIT DACS programs and have conducted our first series of throttling DACS tests recently in 1998.

Four hot-fire test videos are presented to display these accomplishments. The first EXCELS video (Figure 7) documents the 50:1 combustion pressure throttling that is achieved with our pintle thruster control system and propellant. The propellant is ignited and run at full

thrust for 2 sec, throttled down 50:1 out to 19 sec and then throttled back to full thrust for the last second.

The EXCELS hot-fire test shown in Figure 8 demonstrates an extinguishing divert subsystem in a flight configuration. Over a 60 second test period the propellant is ignited and extinguished 3 times to demonstrate repeatability and crispness. The endgame divert operation (third period) demonstrates the ability of the system to deliver smooth proportional thrust changes, square thrust commands, and a short combustion throttling period at the end before a final extinguishment.

The EXCELS hot-fire test shown in Figure 9 demonstrates a full DACS with divert and ACS subsystems integrated into a flight configured envelope. The test demonstrates the ability to thermally manage a continuously pressurized ACS subsystem over 200-sec and to operate the divert and ACS systems together. The test starts with ACS impulse delivery over the first 90 seconds. At that point, the divert propellant is ignited, the divert combustion gases pressurize the ACS and divert chambers together, followed by delivery of a divert impulse out a single thruster. When the divert propellant is extinguished, the ACS accumulator is left fully charged for coast period ACS adjustments.

Later, the divert propellant is ignited again, it pressurizes the two chambers, delivers divert impulse and then is throttled down in pressure. During this 20+ second throttle down period, the flexibility of the divert thrusters is displayed with multiple thrust magnitude and vector changes. The divert combustion pressure is raised back to full pressure at the endgame to demonstrate rapid full thrust pulses that would bring the KW to intercept.

BMDO, the U.S. Navy, Standard Missile Company and the U.S. Army are working with Aerojet to evaluate this technology for their applications. Since mid-1997, we have been under contract to the Standard Missile Company to demonstrate a lightweight throttling EXCELS DACS for the Navy's SM-3 Divert Technology Assessment and Risk Reduction Program. This

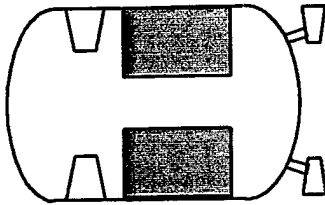
year we began a contract with the U.S. Army SMDC to apply EXCELS technology to the AIT Test Bed Program. Working cooperatively with SM-3 and AIT, Aerojet conducted a hot-fire test of a divert subsystem to validate extension of mission time and multiple throttle periods over a 100 sec duty cycle.

The SM-3 DACS test was conducted at Aerojet in the workhorse combustion chamber shown in Figure 10. The test setup incorporates a flight-shaped propellant grain and flightweight pintles and nozzles to establish propellant ballistics and thruster durability over a 100 sec. duty cycle. Two duty cycle hot-fire tests have been accomplished, one with 4 divert periods and another with 5 divert periods. Figure 11 shows the test firing at a midpoint in the duty cycle where the system is throttled down to coast pressure. Figure 12 shows a trace of the combustion pressure data over the 100 sec duty cycle with 5 divert periods. The trace shows that divert periods

can be performed at anytime during the mission and commanded to differing maximum thrust levels. It also verifies that DACS activity time can be extended over 100 seconds by deep throttling propellant combustion between divert periods. Work is under way on the SM-3 and AIT programs to transition this success to a hot-fire demonstration of a full flightweight DACS.

In conclusion, we have demonstrated EXCELS solid DACS technology breakthroughs that are enabling a new generation of TMD interceptors to be mission flexible, safe and low cost. We are now supporting the Navy's SM-3 and the Army's AIT Programs to adapt EXCELS to new interceptor configurations. In these programs we will improve performance and weight while enabling an increase in kill probability and a reduction in overall KW deployment costs with application of our truly mission flexible EXCELS solid DACS.

Throttling DACS



Extinguishment - Reignition DACS

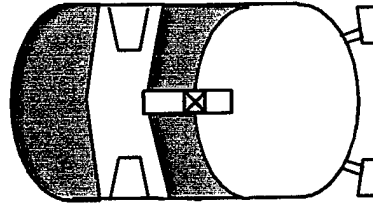
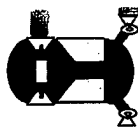
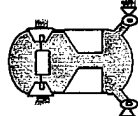


Figure 1. EXCELS DACS Applies to EXO and Endo TMD Missions

**High Combustion Pressure for
Major Divert Periods**



**Throttle to Low Pressure for
Coast Periods**



**Raise Combustion Pressure for
Each Divert Period**

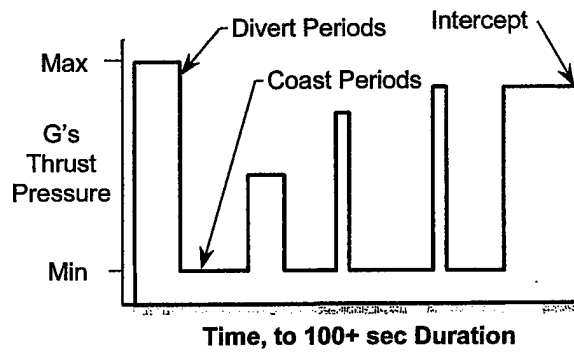
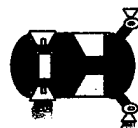


Figure 2. Throttling EXCELS DACS Operation

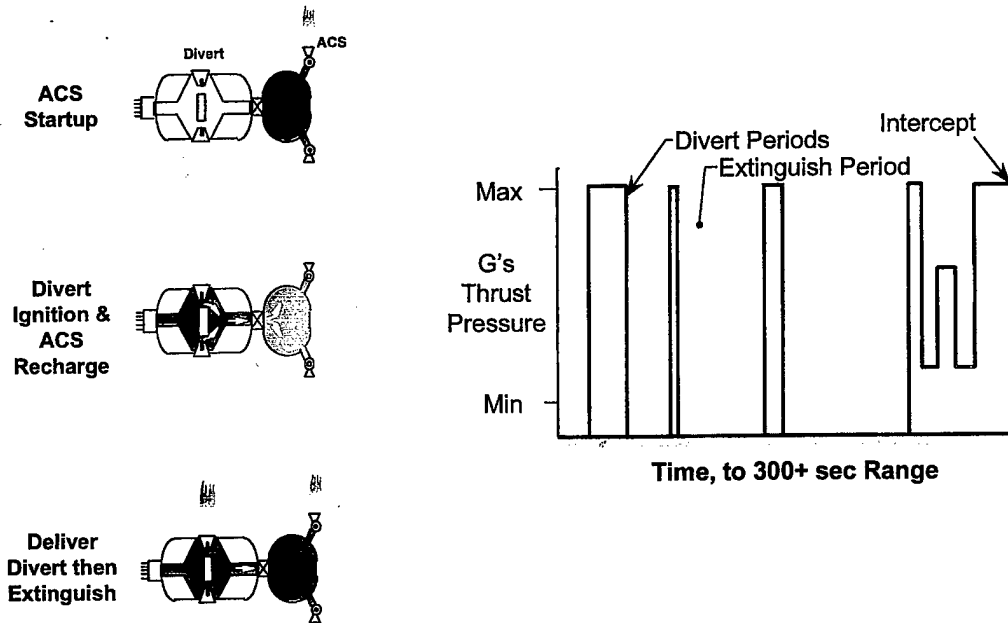


Figure 3. Extinguishing EXCELS Operation

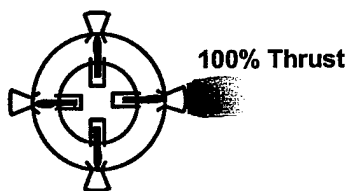
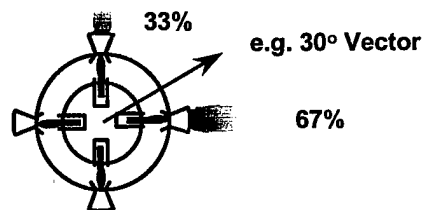
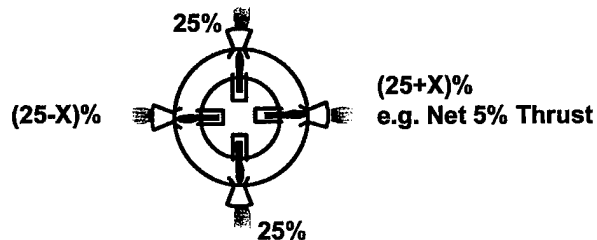
Full Thrust On-AxisVernier Off-Axis ThrustNull Thrust Adjustment for Aim-Point Selection, and JI Adjustment

Figure 4. Proportionally Controlled EXCELS Thrusters Improve Aim-Point Selection, JI Adjustment, and Minimum Impulse Bits

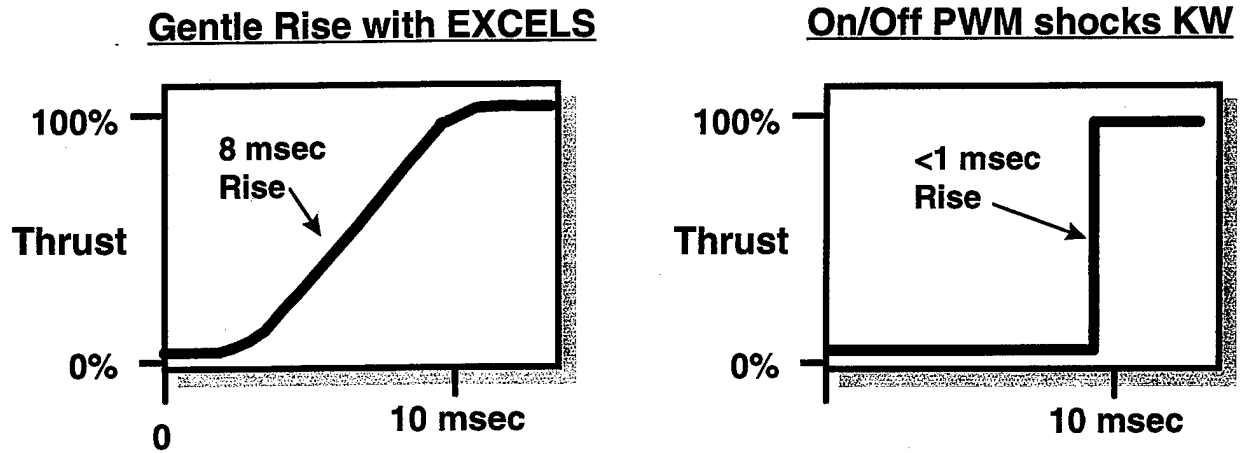
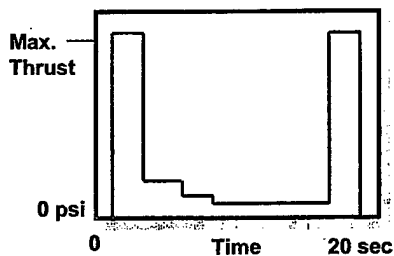
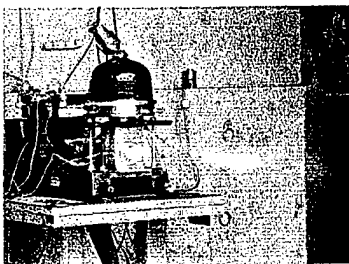


Figure 5. Proportionally Controlled EXCELS Thrusters Deliver "Soft Ride" to KW Seekers and Structure

	91	92	93	94	95	96	97	98
Controlled Pintle Thruster Hot-Fire	██████████							
Multi-Pintle Thruster Hot-Fire		██████████						
Flightweight Divert Hot-Fire			██████████					
Long Duration ACS Hot-Fire				██████████				
Full Flight DACS Hot-Fire					██████████			
SM3/AIT Flight DACS Throttling Hot-Fire							██████████	

Fig



- ◆ Demonstrates 50:1 Pressure Throttling
- ◆ Single 175 lbf thruster
- ◆ Clean Min-smoke Propellant
- ◆ Erosion-Free Pintle Operation

Figure 7. CombustionThrottling Video - #1

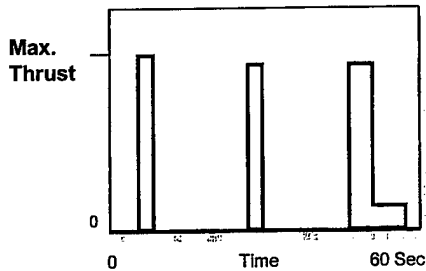
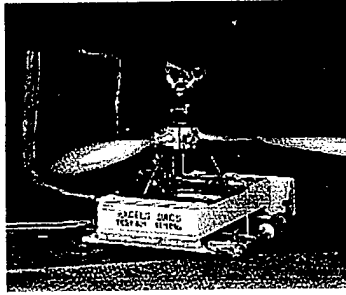


Figure 8. EXCELS DACS IR&D Program Results Extinguishment & Reignition Video - #2

- ♦ Flight configured divert subsystem
- ♦ 3 extinguishments
- ♦ 4 Thruster Divert @ 500 lbf
- ♦ Proportional & PWM in Endgame
- ♦ Pressure Throttling with 4-thrusters at end

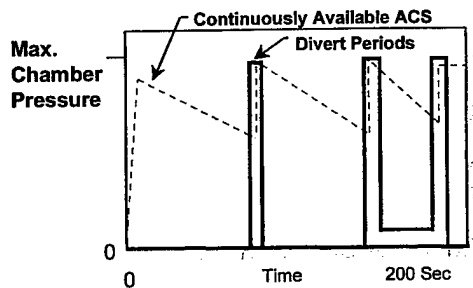
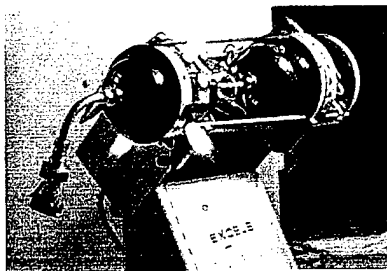


Figure 9. Flight Configured DACS – Video #3

- ♦ 500 lbf divert
- ♦ 200 sec Operation
- ♦ 2 extinguishments
- ♦ 23 seconds throttling
- ♦ ACS Accumulator charged 4 times
- ♦ Independent ACS during Coast

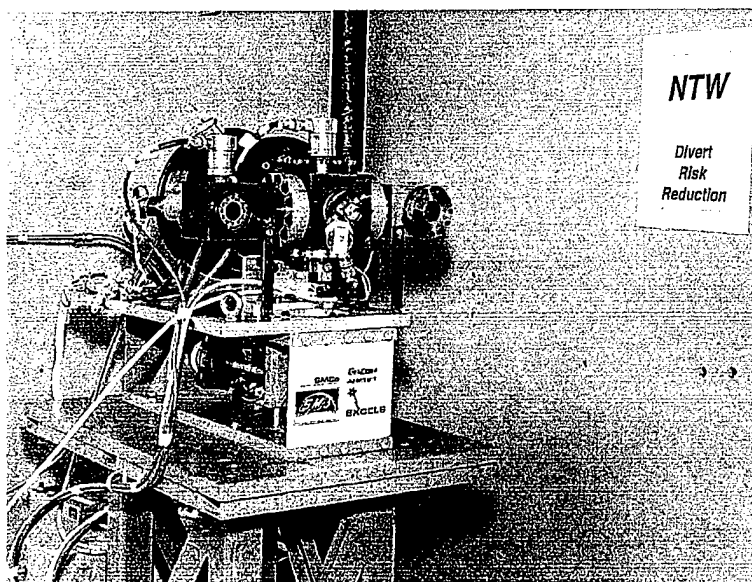


Figure 10. SM3 DACS Workhorse



Figure 11. Video #4 - Combustion Throttling for Propellant Conservation in 100 sec Demo

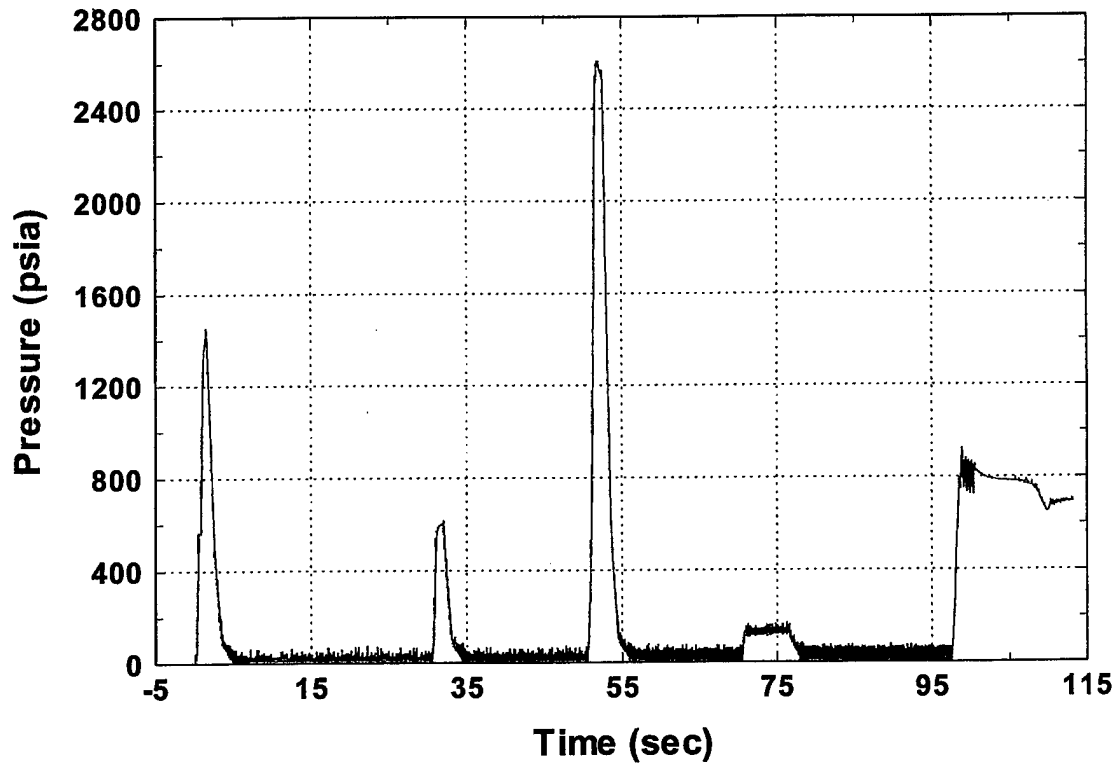


Figure 12. SM-3 Solid DACS - Test 631